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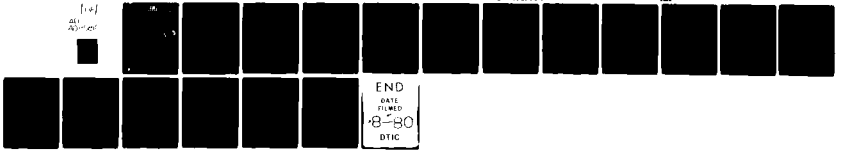

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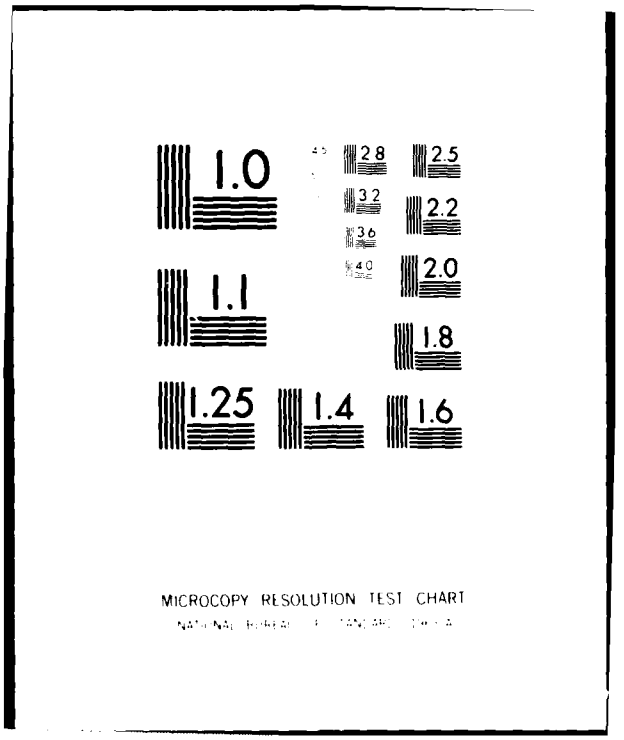
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# ESTIMATION OF LATERAL AND ROTATIONAL CLOUD DISPLACEMENT FROM SATELLITE PICTURES

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Weather forecasting in the mesoscale range often remains problematic due to the rapid changes. With the advance of high-resolution imaging techniques, satellite pictures taken in short time intervals can be employed to improve interpretation and prediction of atmospheric situations by analyzing cloud motion and size parameters. Knowledge of these parameters allows estimation of wind fields as well as the establishment of

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time series in order to model the cloud development and extrapolate from past observations.

Our objective is to find estimators that reveal not only information on lateral (x-y) displacement, but also on rotation of clouds. These estimators should perform well for a variety of meteorological conditions.

Currently, a variety of cloud displacement estimators are competing for computational convenience and versatility in application [1-6]. Our work concentrates on methods applying the Inner Product (popularly called cross-correlation) since we hope to combine a mathematically elegant theory with efficient strategies for application.

Particular emphasis will be directed to:
(1) Improvement of peak detection on the Inner Product surface by pre-filtering of the pictures. This method will be called Accentuated Correlation (AC). An analysis of the given signals and their properties in the spatial and frequency domain leads to the theoretical background of AC. AC will adopt ideas developed for the one-dimensional case [7] and incorporate a recently suggested exponential type of pre-filtering [8]. It can be shown that pre-filtering with a truncated inverse filter leads to better results than the exponential type.

(2) Employing Inner Product methods on the polar-coordinate contour functions of two clouds to determine their relative rotation.

At the time of the workshop, results of the suggested methods will be presented for the case of simple, single clouds. An extension for more complex cloud situations is currently under work.

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## 1) Introduction

Weather forecasting in the mesoscale range often remains problematic due to the rapid development of disturbances. With the advance of high-resolution imaging techniques, satellite pictures taken in short time intervals can be employed to analyze motion and development of clouds. Knowledge of these parameters allows for the estimation of windfields as well as for the prediction of certain types of severe weather situations.

Our objective is to find estimations that reveal information not only of lateral (x-y) displacement, but also of cloud rotation and size changes. The scope of application might well be extended to images of moving objects in general.

Currently a variety of lateral cloud displacement estimators are competing for computational convenience and versatility in application: the film loop technique [1], the "correlation" method [2,3], binary matching [2], clustering analysis [4,5] and relaxation techniques [6].

Our work concentrates on methods applying the inner product (often misinterpreted as cross-correlation), since we hope to combine a mathematically elegant theory with efficient strategies for application in not-too-complex cloud situations.

In this paper, we shall introduce a new pre-filtering technique and suggest a method to identify the rotation of the cloud. A rotating cloud very often indicates a severe weather situation. Conventional inner product methods suffer from poor maximum peak resolution due to cloud shape changes, rotation and other disturbances within the frame of interest. To improve maximum peak detection, pre-filtering of the input images can be performed prior to the inner product operation.

For the case of one-dimensional signals, it has been shown [7] that inverse filtering based on the knowledge of the signal spectrum leads to improvement in certain instances. Recently a complex exponentiated type of pre-filtering was suggested [8]. The method we introduce will be called accentuated inner product (AIP). The pre-filter is a two-dimensional quasi-difference filter with its coefficients determined from the 'auto-inner-product' matrix by solving the Yule-Walker-equations. In comparison with the unfiltered and the complex exponentiated inner product, our empirical studies show the superiority of the AIP.

In estimating the rotation of a cloud, we introduce a method based on the cross-correlation estimate of the polar-coordinate envelope functions.

Finally we suggest the incorporation of simple motion models to derive initial guesses prior to the analysis of the currently received satellite picture in order to cut computation time and allow for fast identification of severe storm situations.

## 2) Signal Analysis and the Inner Product

As conventional prerequisites, the given images are assumed to be discrete in a regular cartesian grid, and the pixels containing a digital brightness value, for example any integer number between 0 (black) and 255 (white). For displacement analysis, all image frames have to be navigated to some reference mark, and, if possible, the brightness of the clouds adjusted for sun angle changes. With the exception of snow-covered terrain, the background usually is darker than the clouds. It is removed by subtracting the threshold value from the picture values. Furthermore, we assume the cloud of interest is completely defined within the image frame.

Since the cloud image sequence $\{x(n,m)\}$ then is zero outside some interval $0 \leq n \leq N-1$ and $0 \leq m \leq M-1$, it belongs to the class of "finite area sequences". Finite area sequences are energy signals, i.e.

$$0 < ||x(n,m)||^2 < \infty \tag{1}$$

with the energy of $\{x(n,m)\}$ defined as

$$||x(n,m)||^2 = \langle x(n,m),\ x(n,m)\rangle = \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} x^2(n,m). \tag{2}$$

These signals describe the $\ell_2$ space with the inner product of two sequences $\{x(n,m)\}$ and $\{y(n,m)\}$, defined as

$$K(0,0) = \langle x(n,m),\ y(n,m)\rangle = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} x(n,m)y(n,m). \tag{3}$$

If the sequence $\{y(n,m)\}$ is displaced by $\nu$ and $\mu$, we obtain

$$K(\nu,\mu) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} x(n,m)y(n-\nu,m-\mu). \tag{4}$$

Note that the cross-correlation is defined as a statistical expected value type of operation involving the joint probability density function. Energy signals are neither stationary nor ergodic. Thus, we shall refer to displacement estimators involving functions like eq. (4) as the inner product method. If $\nu,\mu$ in eq. (4) are varied from 0 ... N-1, 0 ... M-1, there is one set of indices $\hat{\nu},\hat{\mu}$ such that $K(\cdot)$ is maximum.

For the case that $\{y(n,m)\}$ is a shifted version of $\{x(n,m)\}$, i.e.

$$\{y(n,m)\} = \{x(n-n_0, m-m_0)\}, \tag{5}$$

$K(\cdot)$ is maximum for $\hat{\nu} = n_0$, $\hat{\mu} = m_0$. For finite area sequences, the Discrete Fourier Transform can be defined. With $\{X(n,m)\}$ and $\{Y(n,m)\}$ the DFT sequences of $\{x(n,m)\}$ and $\{y(n,m)\}$, Parseval's theorem

$$K(\nu,\mu) = \frac{1}{NM} \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} X(n,m)Y(n,m)e^{i2\pi(\mu m+\nu n)/MN} \tag{6}$$

shows that displacement estimation can also be performed by estimating the phase of the cross spectrum. However, due to the current lack of suitable unwarping algorithms, the evaluation of (4) is preferred to the spectral analysis.

In Fig. 1, the inner product of a one-dimensional square wave signal $\{x(k)\}$ and its shifted version $\{x(k-n_0)\}$ is shown, both somewhat resembling a cloud profile. Note that the resulting triangular function has its maximum at $\tau = n_0$, but is twice as wide as the original function. This effect is well known from the convolution properties. The inner product is at least as wide as the widest of both the input functions.

Since a broad cross spectrum is equivalent to a narrow inner product peak, whitening filters of various kinds were suggested [7] based on the knowledge of the signal spectrum. If that spectrum is invertible, a filter designed to approximate the inverse spectrum would "whiten" the input signals prior to the inner product operation. Recently a nonlinear complex exponentiation pre-filter was suggested [8], of the form

$$x(n,m) \rightarrow \exp(-ipx(n,m)), \tag{7}$$

with p some constant. This pre-filter results in an absolute value inner product

$$E(\nu,\mu) = \left(\sum_{n=0}^{N-1}\sum_{m=0}^{M-1} \cos w\right)^2 + \left(\sum_{n=0}^{N-1}\sum_{m=0}^{M-1} \sin w\right)^2 \qquad (8)$$

with

$$w = p(x(n,m)-y(n+\nu,m+\mu)).$$

The exponential pre-filter was introduced by studying optical transparency properties.

With the series representation

$$e^{-ix} = 1 - \frac{ix}{1!} - \frac{x^2}{2!} + \frac{ix^3}{3!} \ldots , \qquad (9)$$

the exponential pre-filter creates a series of harmonics and thus broadens the spectrum. However, as our results show, it is rather sensitive to object changes.

3) Accentuated Inner Product

In Fig. 2 it is shown that a differentiator-type pre-filter for the example of Fig. 1 leads to a delta-function at $\tau = n_0$. Note that the frequency response of the differentiator is a high-pass, thus this filter removes the dominating low frequencies of energy signals and serves as a whitening filter to some extent.

We introduce the two-dimensional quasi-difference filter

$$y(n,m) = \sum_{i=0}^{1}\sum_{j=0}^{1} a(i,j)x(n-i,m-j) \qquad (10)$$

which, in effect, is a two-dimensional moving average filter of order two.

Its coefficients are chosen by the predictor filter design technique. Thus, the two-dimensional Yule-Walker equations

$$\begin{bmatrix} r(0,0) & r(0,1) & r(1,0) & r(1,1) \\ r(0,-1) & r(0,0) & r(1,-1) & r(1,0) \\ r(-1,0) & r(-1,1) & r(0,0) & r(0,1) \\ r(-1,-1) & r(-1,0) & r(0,-1) & r(0,0) \end{bmatrix} \begin{bmatrix} \gamma(0,0) \\ \gamma(0,1) \\ \gamma(1,0) \\ \gamma(1,1) \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\text{with } r(j,k) = \langle x(n,m),\, x(n-j,m-k) \rangle \,, \tag{11}$$

are solved for the vector $\gamma$. Then, $a(j,k) = -\gamma(j,k)/\gamma(0,0)$ for $j,k \neq 0$, and $a(0,0) = 1$. Note that $\underline{\gamma}$ is the first column of the inverted matrix R. The design of a prediction filter of higher order would be detrimental to the result, since our given signals are in general not of the auto-regressive type, i.e. have no poles. The zero of the quasi-differentiator just cancels the high amount of low-frequencies characteristic to finite area sequences.

Results

In Fig. 3 the inner product surfaces are shown for no pre-filtering (top), exponentiated pre-filtering (middle), and the AIP. The plots in the left column were obtained by performing the inner product of a cloud and its shifted replica. The plots of the right column correspond to cloud pairs with actual changes as observed in a 3-minute interval. For the exponentiated filter, the factor $p = 5$ seemed to give best results. Although the delta peak of the exponentiated inner product for the unchanged cloud is quite impressive, the AIP method seemed to be superior for the case of changing clouds. Since the output is determined for a regular grid, further improvement for estimating the displacement could be achieved by interpolating over the values in the

vicinity of the maximum. A bicubic spline seems to be feasible to obtain the maximum between grid points by solving its derivative for zero.

4) Rotational Displacement Estimation

As indicated above, often it is desired to obtain an estimate of the rotation of the cloud, be it to improve the lateral displacement estimate by turning the image to a best match, or be it for gaining information from the amount of rotation for weather analysis. In the following we assume rotation around a point inside the object, possibly the center of brightness gravity. The detection of the actual axis of rotation, however, still remains a problem, although in many cases the center of gravity or some other reference point commonly recognized in all images of the cloud sequence is sufficient. Fig. 4 shows a contour plot of a cloud for three different gray levels (L=3, 12 and 35, after subtraction of the background level). From these contours and the coordinates of a given point inside, a polar-coordinate envelope is determined by obtaining the distance (radius) to the contour for an equidistant angle domain. Fig. 5 shows the three envelope functions for the cloud in Fig. 4 over the domain 0°-360°, 0° being parallel to the x-axis.

The envelope curves are periodic with periodicity $2\pi$. If a cloud rotates, the envelope functions shift. Hence the amount of rotation can be estimated by estimating the cross-correlation of the envelope functions. Fig. 6 shows the result of a Blackman-Tukey-type cross-correlation of an L = 35 envelope with its rotated successor indicating a maximum at lag 10, i.e. 20° rotation for each lag representing 2°. Note that the peak is more discernible for the L = 12 envelopes. The proposed method is currently tested for its practicability in estimating

rotational displacement. However, the Fourier transform of the envelope function might be of great value for identifying the same cloud in consecutive images.

5) Cloud Motion Modeling

A problem common to all inner product methods is the large amount of computing time necessary to perform the required operations. Computing time can drastically be reduced if an estimate of the cloud motion exists beforehand. Then, the output window can be set as small as possible around the expected surface maximum. On our PDP 11/60, the computing time was reduced to less than a minute for obtaining a 6 by 6 output surface from 128 by 64 pictures, pre-filtering included.

Feasible predictors are currently under research. Our goal is to implement some scalar cloud parameters such as area size, brightness concentration, etc. These are easily obtainable and should be combined with the displacement vectors to low-order models that allow for quasi-real-time cloud state identification and short-time prediction.

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FIGURES.

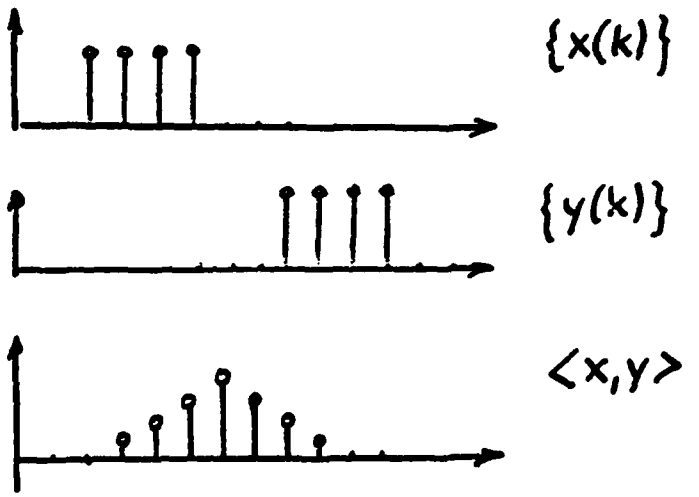


Fig. 1. Inner Product of shifted boxcar functions

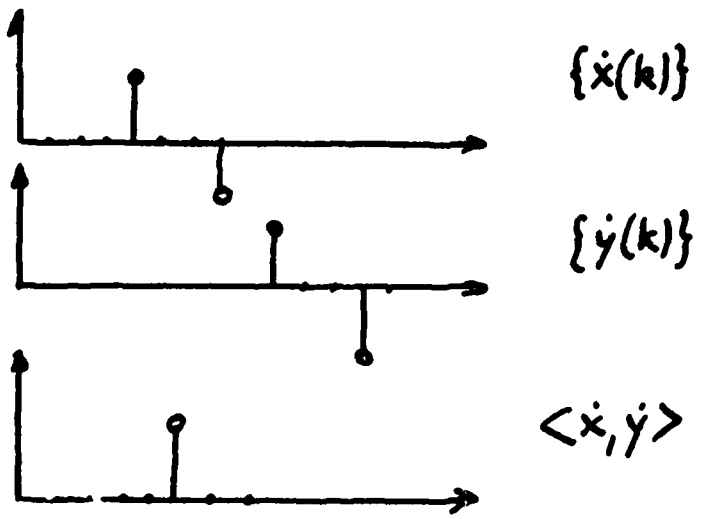


Fig. 2 Inner Product of differentiated boxcar functions

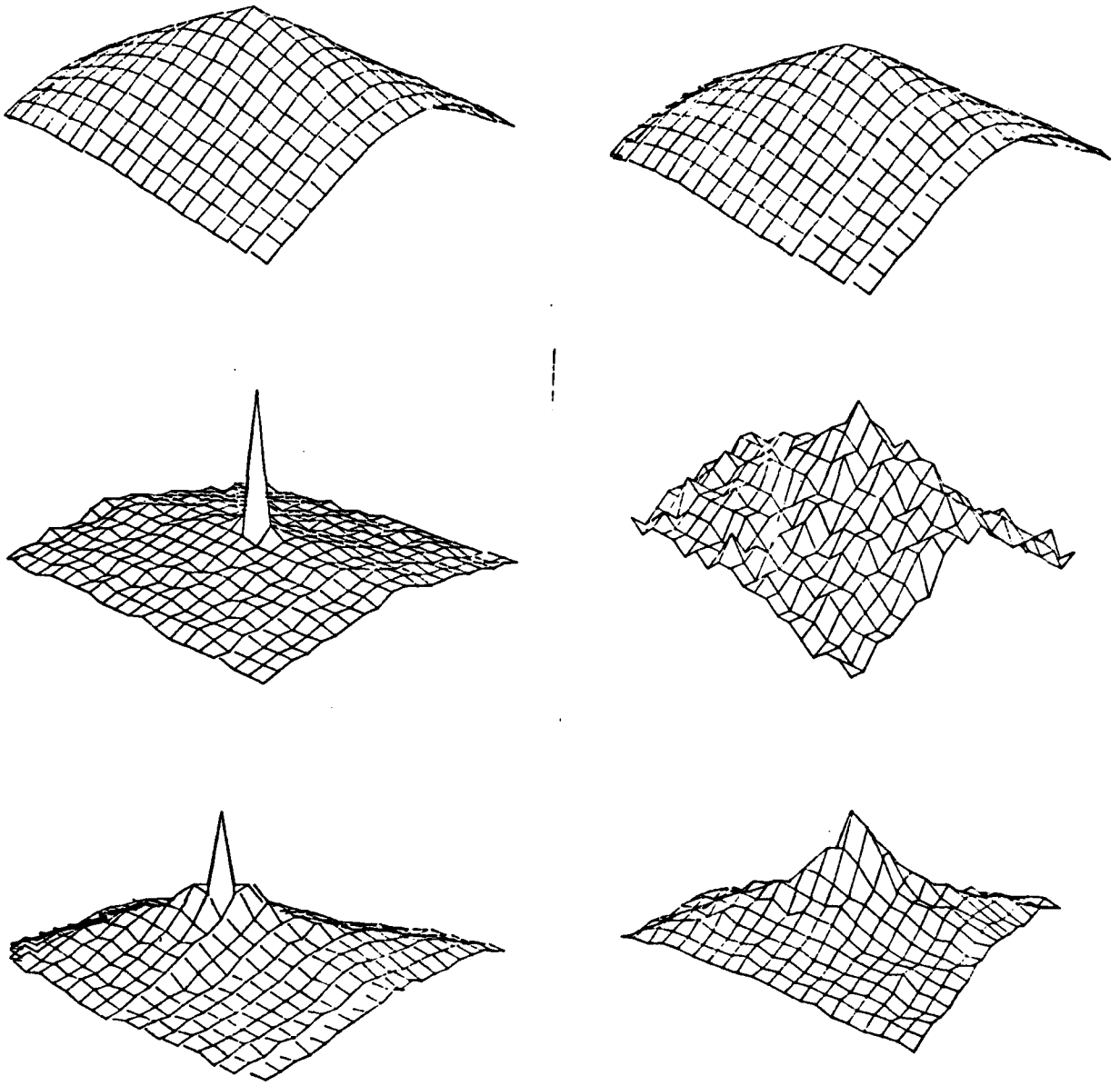

Fig. 3. Inner Product surfaces for unfiltered (top), exponentially (middle) and accentuated (bottom) inputs. Left for unchanged, right for changed cloud.

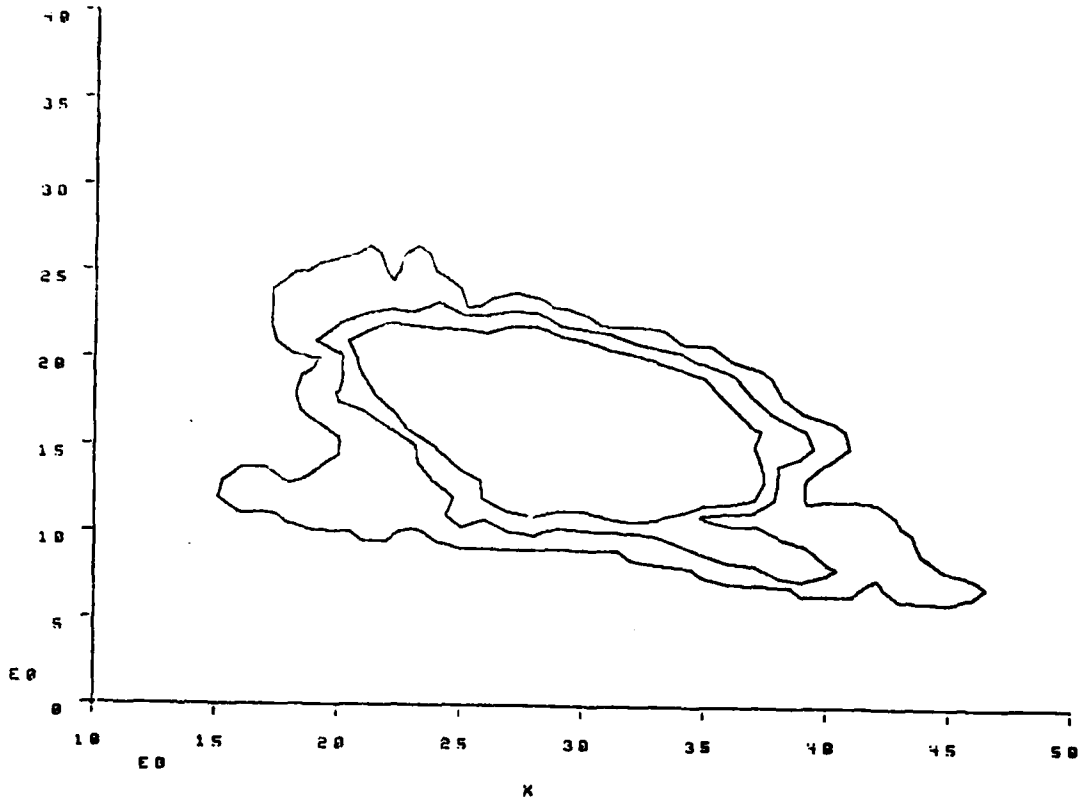


Fig. 4. Contour plots of cloud for brightness levels L = 3, 12 and 35

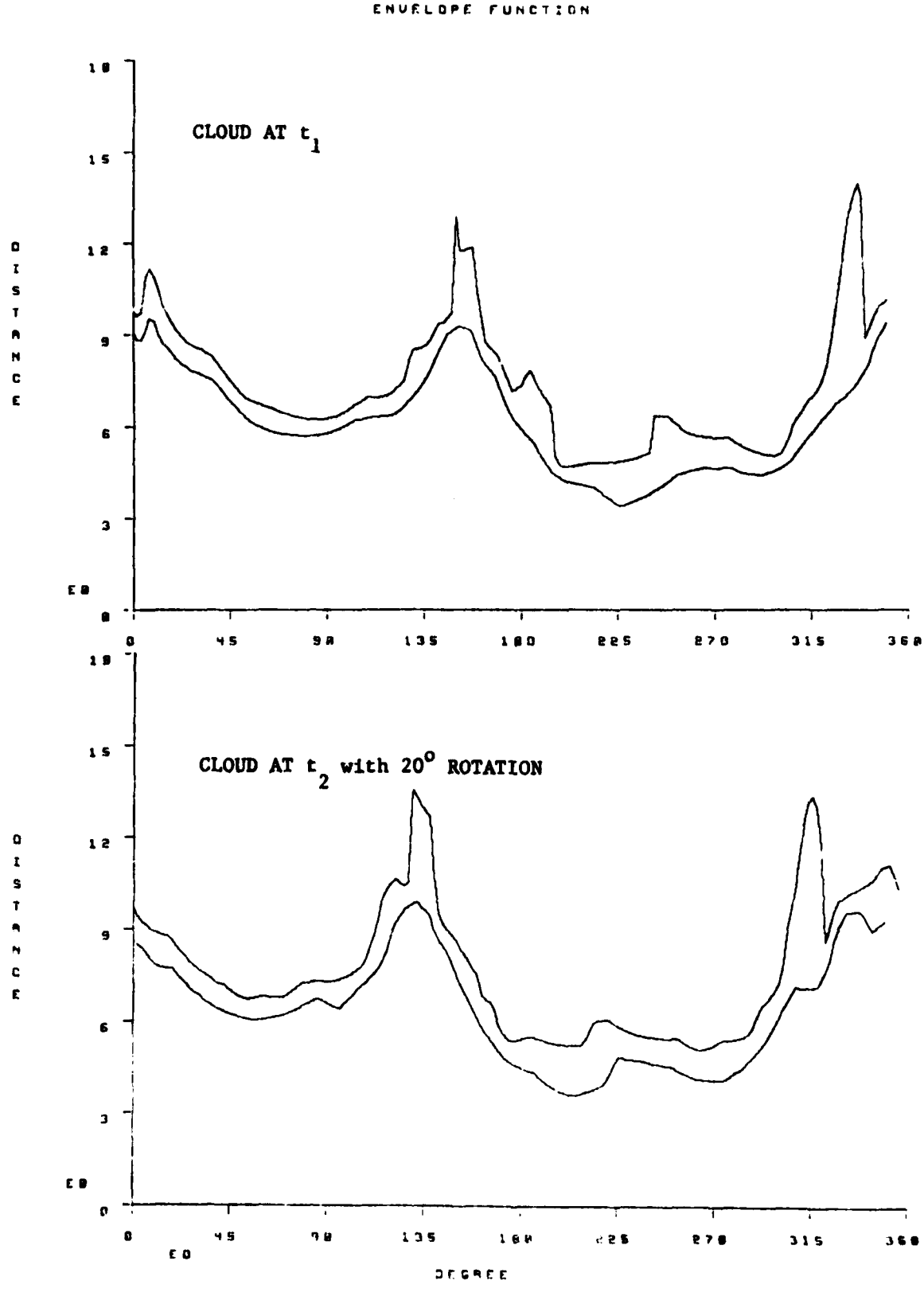


Fig. 5. Polar-coordinate envelope functions

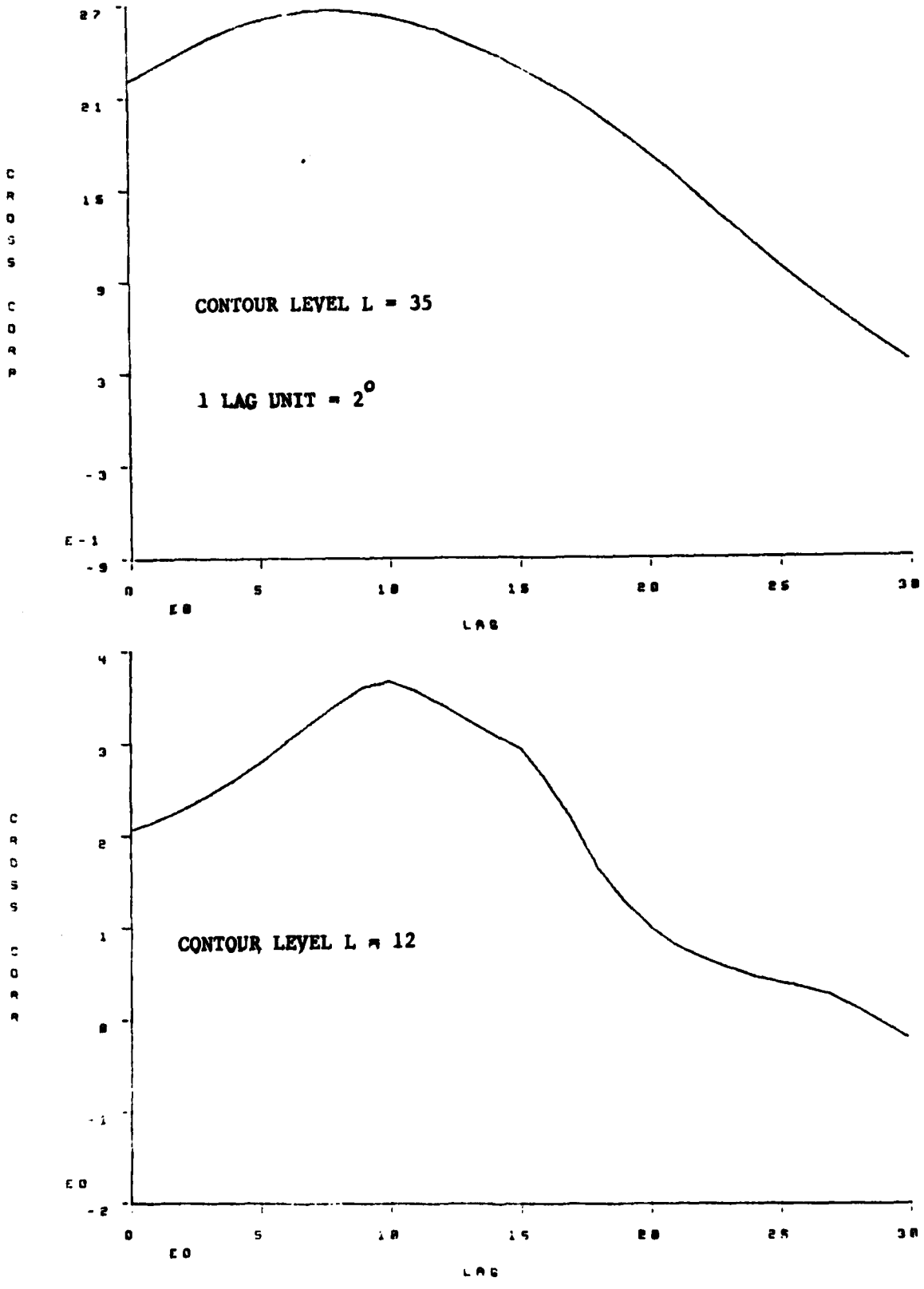


Fig. 6. Cross-correlation estimates of envelope functions.